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In the Application of	)
	) Examiner: *Not Assigned*
Erlend Ronnekleiv, et al.	) Group Art Unit: 2877
	)
Title: FIBER OPTIC SENSOR SYSTEMS	)
	)
Serial No.: 10/017,707	)
	)
Filed On: December 12, 2001	) (Docket No. (6710-04)

Hartford, Connecticut, June 11, 2002

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Sir:

Submitted herewith is a certified copy of the United Kingdom application No. 0030289.3 which was filed on December 12, 2000, in accordance with 35 USC §119 and 37 CFR §1.55(a) to form a part of the above-identified application.

Applicants believe no fee is due for the submission of this priority document, however, if it is determined that a fee is required, please charge deposit account no. 13-0235.

Respectfully submitted,

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1.	Your reference	97.73159
2.	Patent application number *(The Patent Office will fill in this part)*	0030289.3 12 DEC 2000
3.	Full name, address and postcode of the or of each applicant *(underline all surnames)*	Optoplan AS Bjørkhaugvn 27 N-7049 Trondheim Norway
	Patents ADP number *(if you know it)*	06960074002
	If the applicant is a corporate body, give country/state of incorporation	Norway
4.	Title of the invention	Fibre Optic Sensor Systems
5.	Name of your agent *(if you have one)*	Frank B. Dehn & Co.
	"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	179 Queen Victoria Street London EC4V 4EL
	Patents ADP number *(if you know it)*	166001
6.	If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number	Country / Priority application number *(if you know it)* / Date of filing *(day / month / year)*
7.	If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application	Number of earlier application / Date of filing *(day / month / year)*
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73159

Fibre Optic Sensor Systems

This invention relates to fibre optic sensor systems, and relates in particular to improvements in such systems enabling more accurate and higher resolution measurements of optical signals derived from fibre optic sensors.

There are a variety of fibre optic sensors, such as Bragg grating sensors, fibre laser sensors, and interferometric sensors having the potential for measuring small changes in temperature, pressure or strain on or established in an optical fibre. Strains can be induced by physical, chemical or biological parameters, or by electromagnetic fields, and these sensors can be configured to measure accurately a variety of different parameters (measurands). Hence, it is known that optical fibres may be provided with claddings or coatings which react to particular measurands to establish strain within a fibre, this strain changing a detectable optical property of the fibre such that a particular parameter can be measured.

Such sensors are used in medical applications, and in various other applications including engineering and oil and gas exploration.

In relation to such sensors, the varying optical properties of the fibre at one or more sensing locations thereof can be provided by various known means. For example, sensing regions of the fibre may be configured to provide a form of "Fabry-Perot" (F-P) interferometer, whose resonance wavelength when interrogated by a suitable laser light source depends on strain established within the fibre. In such a system there are effectively spaced "mirrors" written into the fibre whose spacing determines the output wavelength which therefore changes with longitudinal strain within the fibre.

and are configured to operate at different nominal wavelengths.

An alternative configuration of sensor involves the use of active fibre lasers, particularly active FBG lasers. Such devices, and interrogating systems therefor, are described in, for example, US 5,844,927 and US 5,564,832. In each of these systems, an end-pumped fibre laser with distributed feedback (DFB) oscillates on two orthogonally polarised wavelengths. The distance between these wavelengths is dependent upon birefringence of a fibre, and is therefore responsive to mechanical strain within the fibre. Such strain can be temperature or pressure dependent, or can be responsive to a variety of different measurands through the use of reactive coatings or claddings on the fibre, for example.

US 5,564,832 and 5,844,927 each describe interrogation systems in which the measurement of birefringence in a fibre laser sensor involves the measurement of electrical beat frequencies established between the different optical frequencies in the mutually orthogonal polarisation planes. As is well known, by superposing two slightly different frequencies together, a lower beat frequency is generated dependent upon the difference between the first two frequencies. The lower frequency regime of the beat frequency enables more convenient measurement of an electrical signal by known processing means.

In US 5,844,927, one or more sensor FBG's are written into birefringent fibres, such that a beat frequency indicative of the wavelength spacing in different polarisation planes for each FBG may be derived. These may be compared with the output signal from a reference FBG laser, which is not written into a birefringent fibre.

The use of a suitably calibrated reference FBG laser is intended to enable accurate measurement of

optic sensor system including measuring and reference sensors written into respective optical fibres, in which at least the reference sensor is written into a birefringent fibre, and the system further includes a detecting means which operates by generating a beat frequency derived from the output of the reference sensor.

A still further aspect of the invention provides a method of sensing using fibre optic sensors, in which the output from a reference sensor provided in a birefringent fibre is used to derive a beat signal for comparison with the output from a measuring sensor provided in a second fibre.

A preferred mode of operation of such a system and method is that a beat frequency derived from the reference sensor output and a beat frequency derived from a comparison between the measuring sensor output and the reference sensor output are used to derive an indication of at least one parameter of interest without the need directly to measure the absolute frequency of either sensor by optical means.

The beat frequency in a birefringent fibre is proportional to the absolute frequency, and the system can be suitably calibrated such that the beat frequency derived from the reference sensor output provides an output indicative of reference sensor temperature, for example.

The beat frequency derived from the comparison between the reference and measuring sensors may then be added to or otherwise compared with this output to derive a further output which is indicative of measuring sensor temperature.

In other words, in such a system, there may be two unknown parameters, for example the measuring and reference sensor temperatures, and two beat signals, namely the reference sensor beat and the beat between the sensor outputs, which can be used to derive a

present invention differ from those described in US 5,828,059 and US 5,564,832, in that the system includes at least one associated pair of measuring and reference sensors provided in different fibres and, in some embodiments, having substantially the same or similar nominal operating wavelengths so that a beat signal is generated between the reference and measuring sensor outputs. The systems may include a number of measuring sensors at different nominal wavelengths and multiplexed along a common respective fibre with a single reference sensor provided in a different fibre or with multiple reference sensors.

As discussed, in one aspect of the invention, the measuring and reference sensors of each pair have the same nominal operating wavelength. This can provide the more accurate and convenient comparison between the reference and measuring spectra. Further, there is no need for optical demultiplexing of the signals from each pair of associated reference and measuring sensors, and demultiplexing can instead be achieved in the electrical domain by processing electronics. This has practical advantages.

The birefringent fibre in which the reference sensor is provided may, for example, be a side-hole fibre, a D-fibre, a Bow-Tie fibre, a Panda fibre, or another fibre with special geometry which establishes a detectable change in birefringence in response to strain and temperature.

The reference scheme of the invention has a number of different applications. It can be used to provide accurate single parameter measurements in relation to pressure, temperature or chemical or biochemical measurands, depending on the configuration of the fibre optic sensor. In this case, the reference sensor can be used for temperature compensation, for example. The frequency splitting in relation to the optical output from the birefringent reference sensor can be accurately

notch, derived from the or each measuring sensor, and compare this with a signal based on the birefringent output of the reference sensor e.g. to generate a beat signal between the measuring and reference sensor outputs in the manner described above. Two independent single frequency sensors may be used, with the system analysing the difference in wavelength between the sensors.

In the presently preferred embodiments, the or each measuring sensor is also provided in a birefringent fibre, and provides a birefringent response in relation to which measurement can be based on the absolute frequency of the response, and/or on the spacing of spectral peaks or notches in mutually orthogonal polarisation planes. This spacing can be compared with the birefringent wavelength spacing derived from the reference sensor, such that the reference sensor can be used to calibrate or correct the output from the measuring sensor. Additionally or alternatively, the absolute frequency of the measuring sensor output can be used for measurements. This enables highly accurate dual parameter measurements to be made, where two parameters, such as pressure, temperature, or biochemical parameters, can be determined by measuring the absolute frequency of the measuring sensor, the absolute frequency of the reference sensor, together with the birefringent frequency splitting of each of these sensors. As discussed above, the absolute frequency of the measuring sensor may itself be derived from beats generated between the measuring and reference sensor outputs.

In one set of embodiments the reference and measuring sensors are in the form of active fibre lasers, preferably fibre DFB lasers. At least the reference laser, and preferably also the measuring laser, is/are written into a birefringent fibre, such that the outputs each consist of spaced spectral peaks

and detecting means configured to generate beat signals dependent upon the birefringence of said at least one fibre, the detecting means preferably also generating beat signals between the laser outputs, which beat frequencies are used to derive a measurement of at least one parameter.

As discussed above, in this aspect, one of the fibre lasers may constitute a reference laser which is located in a separate environment from a measuring laser. Alternatively, pairs of lasers may be located in the same environment, in differently configured fibres.

In a different set of embodiments, the sensing system is based on a passive device, preferably a passive fibre Bragg grating, most preferably a π-phase-shifted FBG. In this case, at least the reference sensor is provided in a birefringent fibre, and the two resonances corresponding to the birefringent axes of the fibre are measured.

This measurement may be carried out in a manner which is generally similar to that described in US 6,097,487, in which a comb spectrum derived from part of the light from a tunable light source is generated, and this comb spectrum provides an accurate frequency/wavelength scale for measurement of the spacings between the spectral notches in the birefringent output of the fibre. Examples of suitable tunable light sources are tunable single polarization lasers or a tunable side band of an RF modulated laser.

In a preferred such system, the comb spectrum is generated by an interferometer which receives a part of the light from the tunable source, and is also effective to reduce the effect of noise in the output of the tunable source, which can otherwise limit the resolution of spectral measurements.

Such a system provides an improved apparatus for measurement of reflection and absorbent spectra enabling particularly high resolution.

fibre.

A further aspect of the invention provides a detecting means for use with a fibre optic sensing system, the detecting means including means for receiving and analysing optical outputs from at least two fibre optic sensors, which outputs have substantially the same nominal operating wavelength, and at least one of the outputs having birefringent components, the analysing means operating by comparing said outputs from the respective sensors to derive an output signal indicative of at least one parameter sensed by at least one of the sensors in use.

A further aspect of the invention provides a method of sensing a parameter through the use of a fibre optic measuring sensor in which the optical output from the sensor is compared with the optical output from a reference sensor, the reference sensor being provided in a birefringent fibre and said sensors having substantially the same nominal operating wavelength.

A still further aspect of the invention provides a dual parameter fibre optic sensing system, comprising a pair of birefringent optical fibres each having at least one sensor configured to provide a birefringent optical output dependent upon a respective parameter, and detecting means having signal processing means adapted to provide an electrical output signal indicative of the birefringence of each of said fibre.

In this, and some other embodiments of some of the above aspects of the invention, the sensors may instead be configured to operate with substantially different operating wavelengths to avoid cross-talk in the detection means.

Some preferred embodiments of the invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1a shows a preferred embodiment of a two-parameter sensor system comprising two dual-polarisation

Figure 7 illustrates a spectra measured through a specific setup according to Figure 4a.

Figure 1a shows a two-parameter fibre optic sensor system based on two birefringent i.e. dual-polarisation fibre DFB laser sensors, where two independent parameters are determined from the frequency splitting and the absolute optical frequency of one of the fibre DFB lasers 1, acting as the measuring sensor, using the other laser 2 as a reference sensor. Laser 1 is contained in a sensing probe house 3. The two lasers 1 and 2 are spliced to the two output ports 4 and 5 of a polarisation maintaining 2x2 coupler (PMC) 6 such that the two orthogonally polarised laser frequencies emitted from each laser are guided in each of the two orthogonal polarisation axes of the polarisation maintaining output ports 4 and 5 of the PMC. The fibre lasers, which have the same nominal operating wavelength, are pumped by a semiconductor diode 7, which can have a pump wavelength of 980nm or 1480nm, through an optical isolator 8 spliced to one of the input ports 9 of the PMC.

The two orthogonally polarised laser frequencies emitted from each laser, ν_1 and $\nu_1+\Delta\nu_1$ from laser 1 and the ν_2 and $\nu_2+\Delta\nu_2$ from laser 2 (see Fig. 1b), are guided through the PMC to the port 10, which is spliced to polarising optical isolator 12 with polarisation maintaining fibre pigtails. The splice 11 is arranged with the polarisation axes of the two fibres oriented at 45° such that orthogonally polarised laser light is mixed.

The laser light passing the isolator 12 is incident on a detector 13 followed by an electrical receiver circuit 14 with electrical receiver bandwidth BW, where the orthogonally polarised laser light is mixed to generate three electrical beat frequencies $f_1 = \Delta\nu_1$, $f_2 = \Delta\nu_2$ and $f_3 = \Delta\nu_{12}$ (see Fig. 1b), where f_1, f_2, $f_3 < BW$. The beat frequency f_3 is a measure of the laser frequency of laser 1 relative to the laser frequency of reference

and $\nu_2+\Delta\nu_2$ from laser 2 (see Fig. 1b), are guided through the PMC to the port 10, which is spliced to polarising optical isolator 12 by means of polarisation maintaining fibre pigtails. The splice 11 is carried out with the polarisation axes of the two fibres oriented at 45° such that orthogonally polarised laser light is mixed. The laser light passing the isolator 12 is incident on a detector 13 followed by an electrical receiver circuit 14 with electrical receiver bandwidth BW, where the orthogonally polarised laser light is mixed to generate two electrical beat frequencies $f_1 = \Delta\nu_1$ and $f_2 = \Delta\nu_2$ (see Fig. 1b), where f_1 and $f_2 <$ BW. Note that $\nu_2 - (\nu_1+\Delta\nu_1)$ can, in this embodiment, be > BW to prevent a beat signal being generated between the two lasers. The electrical beat frequencies f_1 and f_2 provide exact information about the two parameters to be measured, provided the two lasers are under equal temperature and strain conditions.

Alternatively, a beat signal may additionally be measured between the lasers. Such a signal can be used to monitor, e.g. anomalies in the sensor probe.

Figure 3 shows a distributed sensing system where a series of dual-polarisation fibre DFB lasers 1 and 2 contained in pairs in sensor probes 3 are wavelength multiplexed along two different polarisation maintaining fibres with laser wavelengths λ_i, i=1,2,3,4. The two fibres are spliced in the two output ports 4 and 5 of a polarisation maintaining 2x2 coupler (PMC) 6 such that the two orthogonally polarised laser frequencies emitted from each laser are guided in each of the two orthogonally polarisation axes of the polarisation maintaining output ports 4 and 5 of the PMC. The fibre lasers are pumped by a semiconductor diode 7, which can have a pump wavelength of 980nm or 1480nm, through an optical isolator 8 spliced to one of the input ports 9 of the PMC. The two orthogonally polarised laser frequencies emitted from each laser are guided through

minimise the wavelength separation between the two FBGs, and hence the required laser tuning range , and to minimise temperature variations of the reference FBG.

The laser light passes an optical isolator 106 before it is split by a direction coupler 107, where one part is again split by a 50/50 coupler 108 and directed to FBG 101 and 102 through polarisation controller (PC) 109 and 50/50 coupler 111, and PC 116 and 50/50 coupler 112, respectively. The polarisation controllers are used to align the polarisation of the laser light at 45° relative to the two orthogonal polarisation axes of each FBG. The second part of the light split by coupler 107 is passed to a reference Michelson interferometer 113, which is packaged such that rapid temperature fluctuations are minimised. The interferometer consists of a 50/50 coupler 114, two fibre arms 115 and 116, with a path imbalance ΔL, which is typically 10-100m, with Faraday mirrors 117 and 118 at the end of each fibre arm.

The use of Faraday mirrors eliminates polarisation fading in the reference interferometer. The reflected light from the reference interferometer 113 is passed to a reference detector 119. The detected reference signal consists of a pulse train 120 with equidistant peaks corresponding to the free spectral range of the reference interferometer. The reflected light from the FBGs 101 and 102 are directed to detector 121 and 122 through coupler 111 and isolator 123, and coupler 112 and isolator 124, respectively. The detector signals are the result from scanning the two orthogonally polarised spectra of the high finesse π-phase-shifted FBG, illustrated in Fig. 4b at 45°, with solid and dotted lines, respectively. The resulting spectrum is shown in Fig. 4c, clearly showing two narrowband dips in the spectrum, which separation is directly proportional to the fibre birefringence.

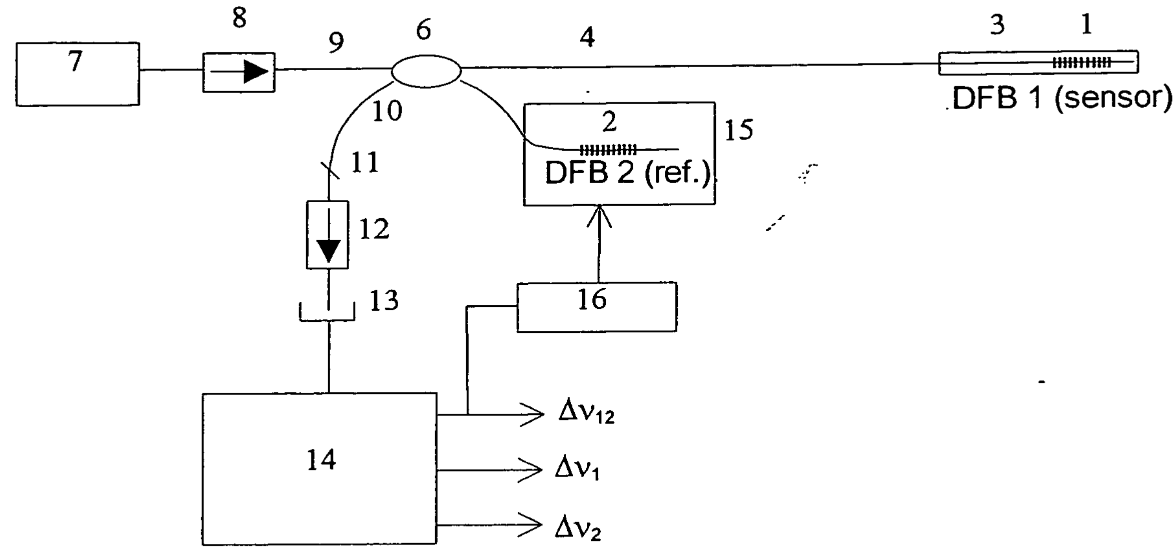
By comparing the detector signals from detector 121

diode laser. The reflected light from the FBGs 101 and 102 is directed to separate detectors 121 and 122, through wavelength demultiplexers 126 and 127, for the sensor and reference wavelengths, respectively. Only one of the laser wavelengths is directed to the reference Michelson interferometer 113 by using a WDM coupler or filter 125, which is sufficient to linearise the wavelength sweep provided that all wavelengths are swept equally.

In an alternative to the embodiment shown in Figure 6, a single tunable laser tuning all sensor wavelengths may be used. In this case only a single reference sensor may be used.

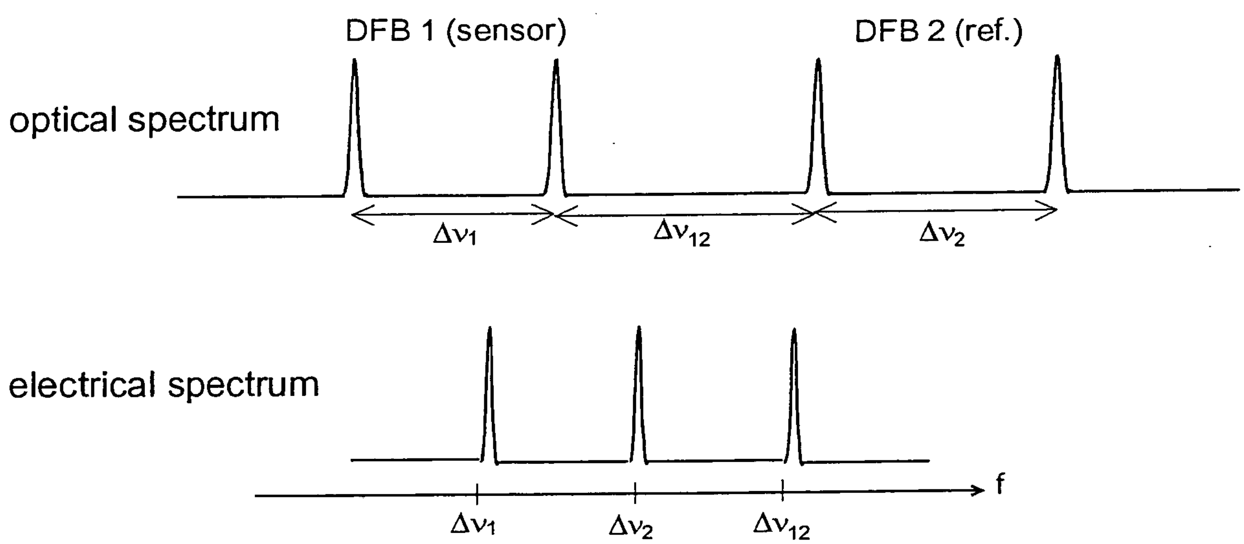
Figures 7a and b, show the simultaneously measured reflection and transmission spectra of a birefringent π-phase-shifted FBG (device under test - DTU) 101 using a setup very similar to the one illustrated in Fig. 4a, illustrating how the setup can be used as an ultra-high-resolution optical spectrum analyser for characterisation of wavelength dependent optical components such as FBGs.

In a particular embodiment, the frequency swept narrowband laser 104 shown in Fig. 4a is a strained tuned single polarisation fibre DFB laser polarised at 45° relative to the polarisation eigenaxes of the FBG. The reference Michelson interferometer 113 has a path length imbalance of ca. 30m, which gives sinusoidal fringes (comb spectrum) with a periodicity of ca. 3MHz. The reference fringes are used to sample the laser frequency and hence linearise the frequency scale and reduce the effect of the laser frequency noise on the measured spectra. The transmission spectrum of the FBG 101 is measured with a separate optional detector 125 at the output end of the FBG. Fig. 7a shows the measured spectrum over the full bandwidth of the FBG (ca. 16GHz or 0.13nm), while Fig. 7b shows a close-up of the two orthogonally polarised resonances, which have splitting



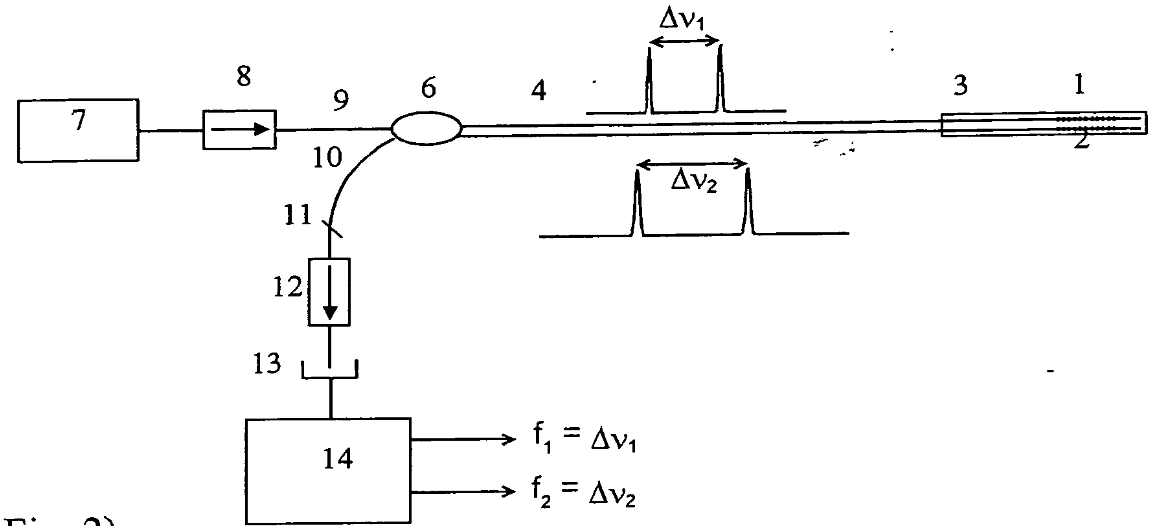
7
8
9
6
4
3
1
DFB 1 (sensor)
10
2
15
11
DFB 2 (ref.)
12
13
16
14
Δν12
Δν1
Δν2

Fig. 1a)



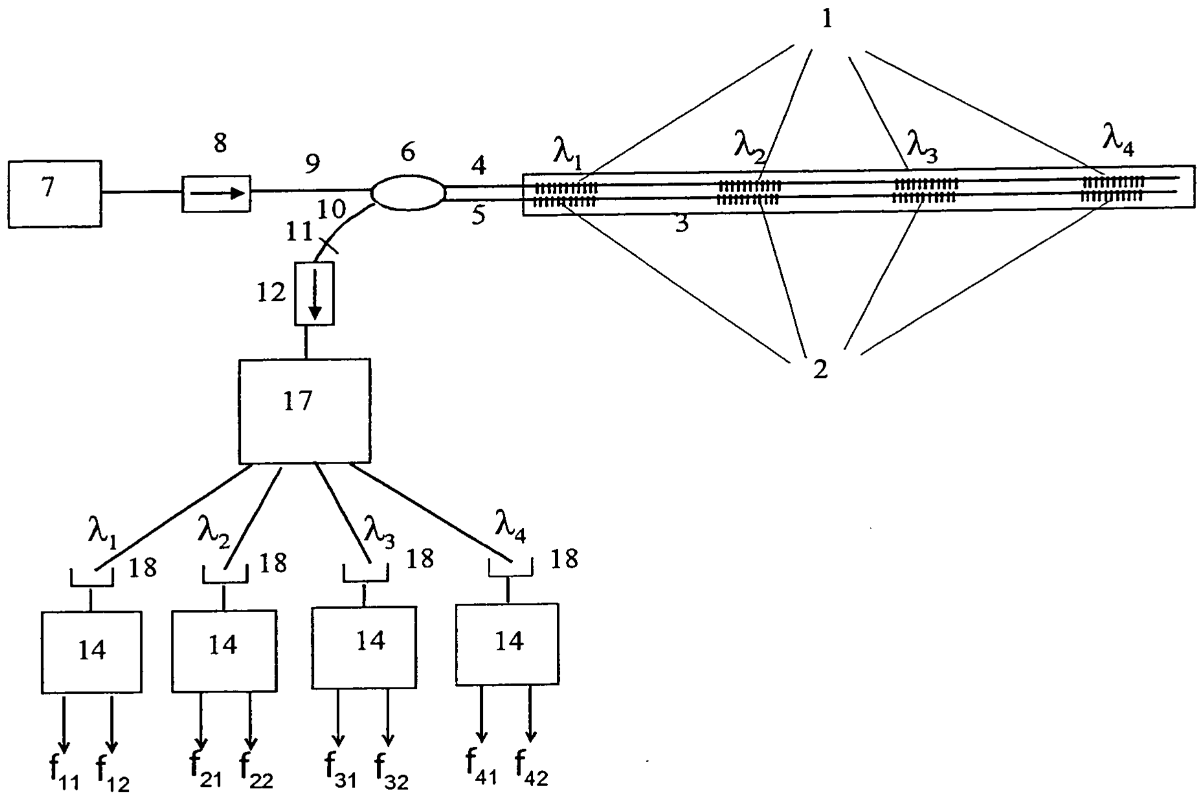
DFB 1 (sensor)
DFB 2 (ref.)
optical spectrum
Δν1
Δν12
Δν2
electrical spectrum
f
Δν1
Δν2
Δν12

Fig. 1b)



Δν1
8
9
6
4
3
1
7
2
10
Δν2
11
12
13
14
$f_1 = \Delta\nu_1$
$f_2 = \Delta\nu_2$

Fig. 2)



1
8
9
6
4
λ1
λ2
λ3
λ4
7
10
5
3
11
12
2
17
λ1
λ2
λ3
λ4
18
18
18
18
14
14
14
14
f_{11} f_{12}
f_{21} f_{22}
f_{31} f_{32}
f_{41} f_{42}

Fig. 3)

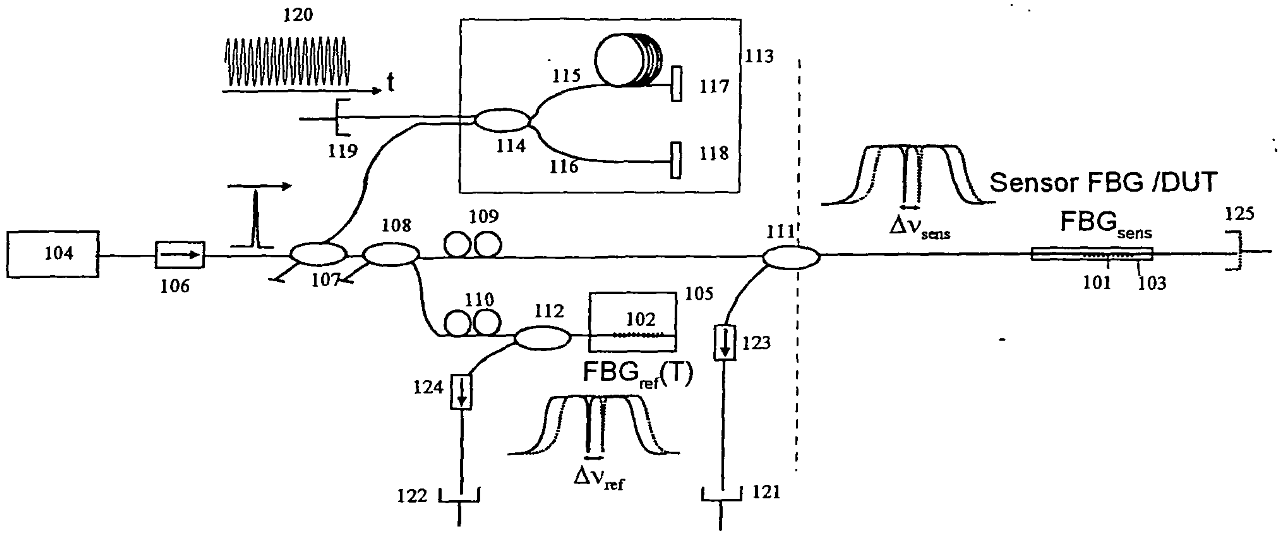

120
t
113
115
117
114
119
116
118
Sensor FBG /DUT
104
106
107
108
109
111
$\Delta\nu_{sens}$
FBG_{sens}
125
101
103
110
112
102
105
123
124
$FBG_{ref}(T)$
$\Delta\nu_{ref}$
122
121

Fig. 4a)

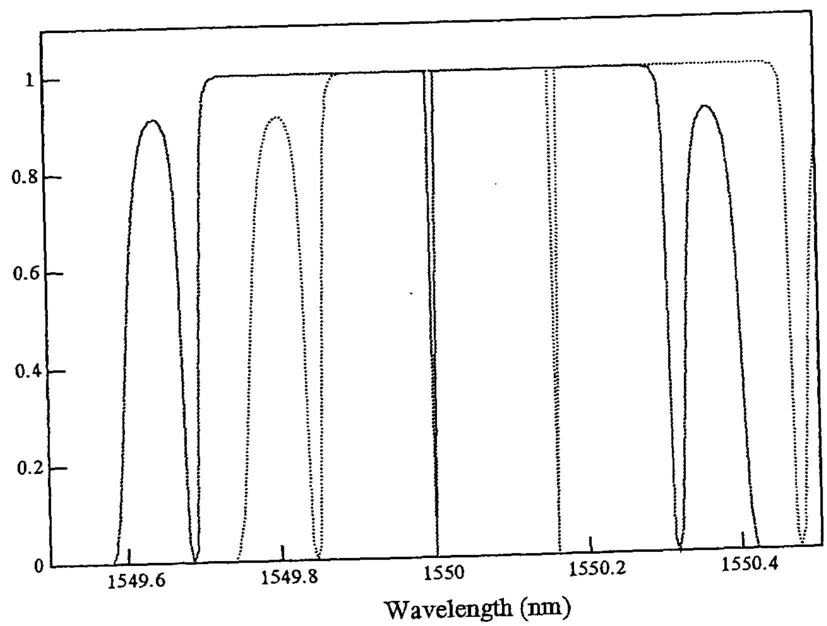
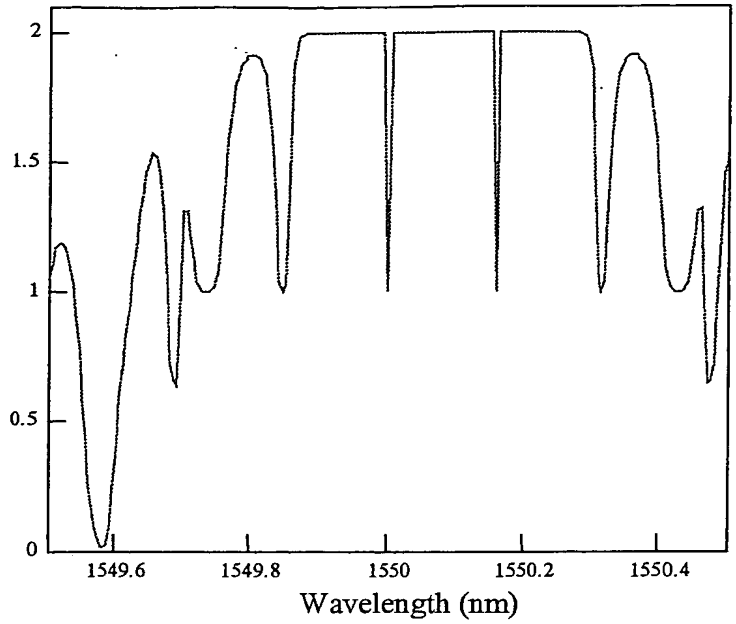
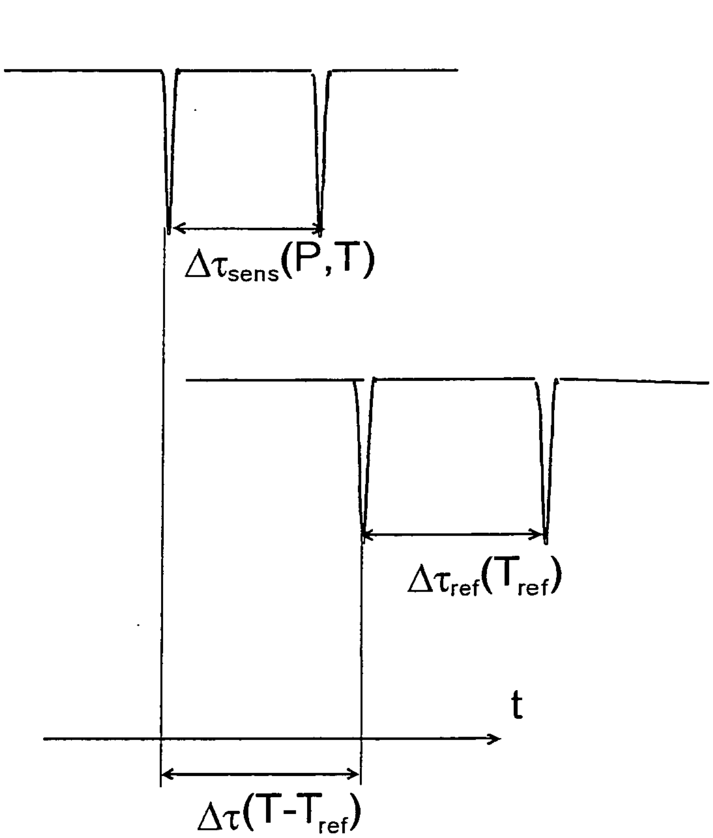

1
0.8
0.6
0.4
0.2
0
1549.6
1549.8
1550
1550.2
1550.4
Wavelength (nm)

Fig. 4b)



2
1.5
1
0.5
0
1549.6
1549.8
1550
1550.2
1550.4
Wavelength (nm)

Fig. 4c)



$\Delta\tau_{sens}(P,T)$
$\Delta\tau_{ref}(T_{ref})$
t
$\Delta\tau(T-T_{ref})$

Fig. 4d)

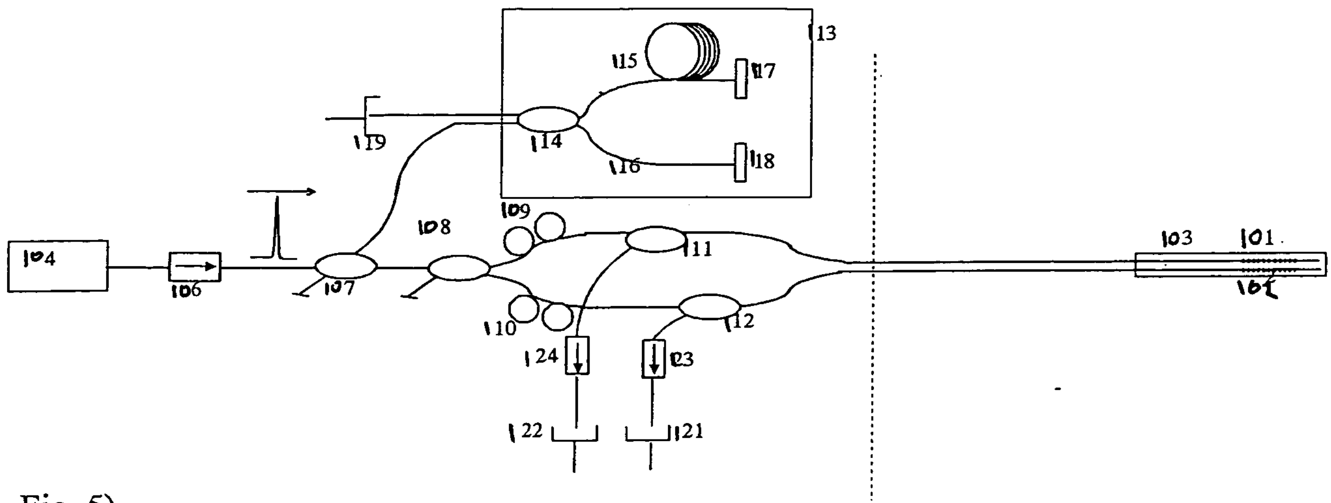

113
115
117
119
114
116
118
109
108
104
106
107
111
103
101
102
110
112
124
123
122
121

Fig. 5)

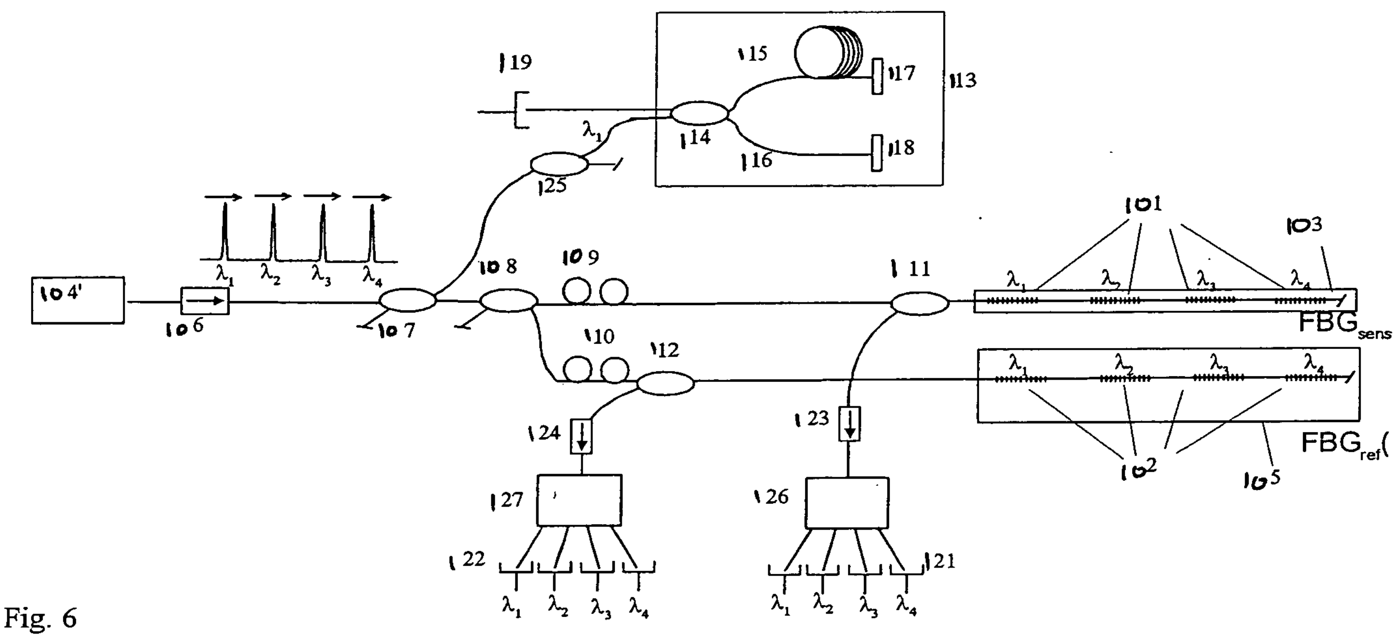

119
115
117
113
λ_1
114
118
116
125
101
103
λ_1 λ_2 λ_3 λ_4
104'
106
107
108
109
111
FBG$_{sens}$
110
112
124
123
FBG$_{ref}$
102
105
127
126
122
121
λ_1 λ_2 λ_3 λ_4

Fig. 6

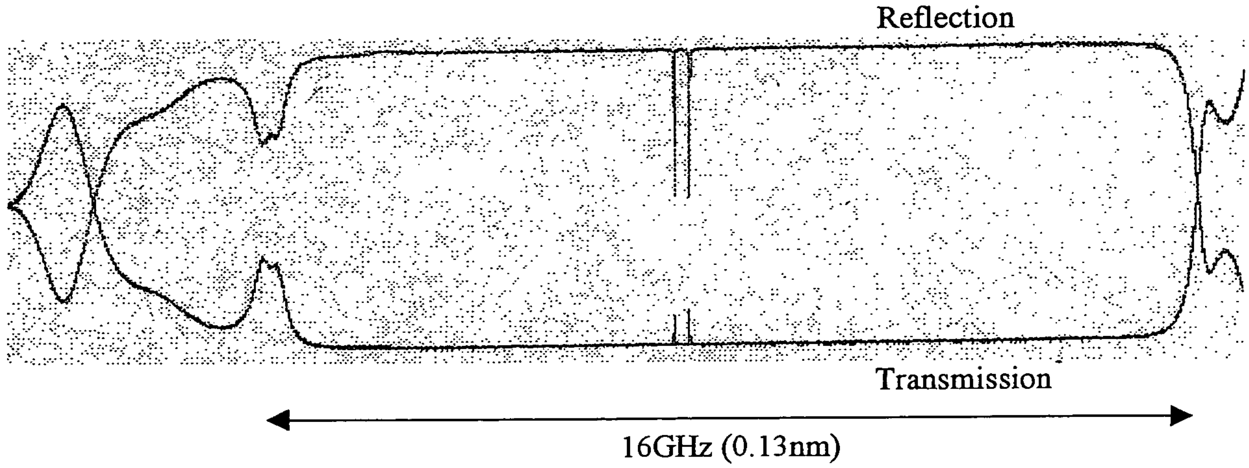


Fig. 7a)

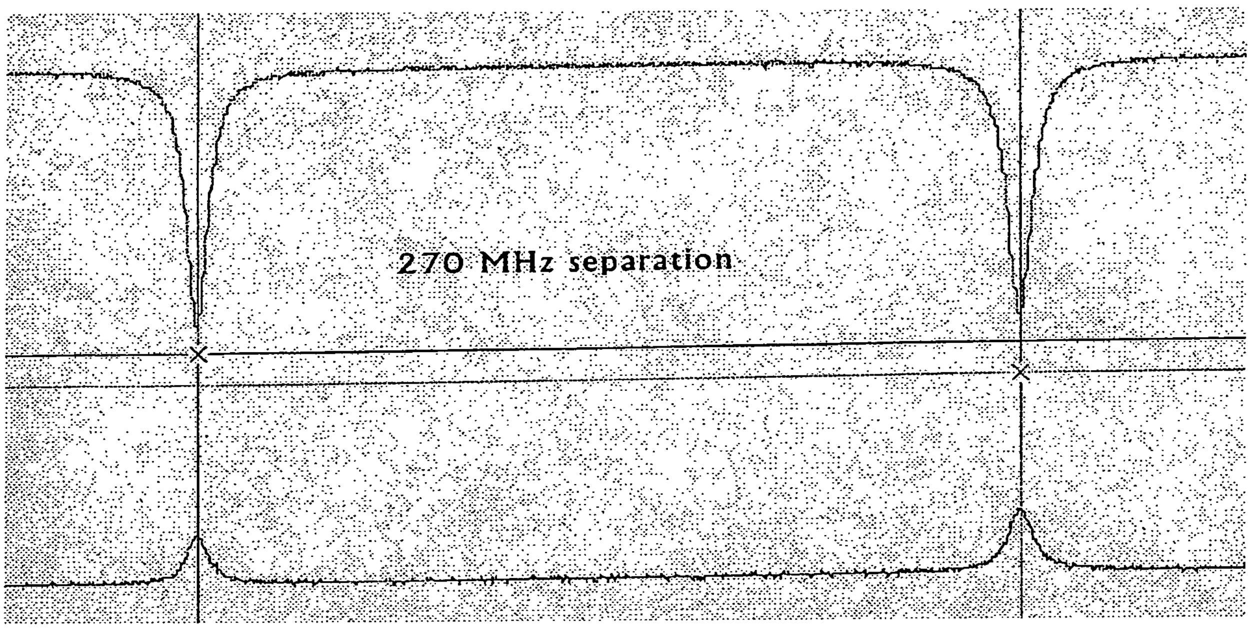


Fig 7b)